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LLNL Preliminary Design for BeRP Ball with Composite Polyethylene and Nickel Reflection

IER-203 CED-1 Report

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Auspices
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0.0 Executive Summary

Composite reflection effects, where a combination of two reflectors act in concert to produce more reactive nuclear systems than either single reflector material separately, is a little known anomaly of criticality safety. The Lawrence Livermore National Laboratory's (LLNL's) Nuclear Criticality Safety Division encountered this anomaly in calculations completed to support fissile material operations. In FY2014, the U.S. Department of Energy (DOE) Nuclear Criticality Safety Program (NCSP) approved and funded the preliminary design for Integral Experiment Request (IER) 203, Composite Reflection Experiments, to focus on preliminary design of critical experiments to experimentally investigate this computational result. This report fulfills the requirements of Critical Experiment Design (CED)-1 and demonstrates the feasibility of creating a critical configuration with the Beryllium Reflected Plutonium (BeRP) ball reflected by a combination of polyethylene and nickel.

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1.0 Introduction

The Lawrence Livermore National Laboratory's (LLNL's) Nuclear Criticality Safety Division, in support of fissile material operations, calculated surprisingly reactive configurations when a fissile core was surrounded by a thin, moderating reflector backed by a thick metal reflector. These composite reflector configurations were much more reactive than either of the single reflector materials separately. The calculated findings have resulted in a stricter-than-anticipated criticality control set, impacting programmatic work. In FY2014, the U.S. Department of Energy (DOE) Nuclear Criticality Safety Program (NCSP) approved and funded the preliminary design for Integral Experiment Request (IER) 203, Composite Reflection Experiments, to focus on preliminary design of critical experiments to experimentally investigate this computational result. This report fulfills the requirements of Critical Experiment Design (CED)-1 and focuses on the Beryllium Reflected Plutonium (BeRP) ball as a fissile material core reflected by polyethylene and nickel.

2.0 Previous Work

When analyzing an operation for safety, nuclear criticality safety engineers often determine a bounding level of reflection expected to be experienced by the fissile material. If the operation has multiple reflector materials present, a common method for assessing the reflection is to employ experimental data or a computational method to set the criticality safety limit based on the single best reflector alone. This approach assumes that the different reflector materials do not act in concert to reduce the critical mass more than a homogenous reflector. While this is sometimes a conservative assumption, review of historical criticality experimentation and scientific literature reveals a few studies that have shown composite reflectors to be more effective than single reflectors.

The *Anomalies of Criticality Safety*[1] contains a short, two page section on "Complex Reflectors," which cautions that combinations of reflectors can be more reactive than the reflectors separately. The report briefly describes two cases of composite reflectors. The first case showed the combined effect of nickel backed by depleted uranium on the critical mass of a uranium hydride core. These experiments were completed by Paxton, and the published account of the work demonstrated that a composite reflector of 1.27 cm thick Ni backed by 20 cm of depleted uranium yielded a smaller critical mass than either reflector separately[2]. The second case reported in the *Anomalies* results from critical experiments at Pacific Northwest National Laboratory (PNNL) that looked at arrays of low enriched UO_2 rods with 2 cm of water reflection backed by 7.6 cm of depleted

[1] Clayton, E.D. *Anomalies of Criticality Safety, Revision 6*. Pacific Northwest National Laboratory. PNNL-19176. February 2010.
[2] Paxton, H.C. et al. "Enriched Uranium Hydride Critical Assemblies." *Nuclear Science and Engineering*. Vol 7, p 44, 1960.

uranium. This combination of reflectors was shown to be more effective than either a thick water reflector or a depleted uranium reflector backed by water.

The International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook[3] includes the PNNL experiments mentioned in the above as a benchmark. However, since the assembly was low enrichment, the benchmark is a thermal system. The effect of the composite reflector is likely much less dramatic in a thermal system than in a fast metal system where the hydrogenous reflector moderates faster neutrons. There are a few other ICSBEP benchmarks that look at “compound reflectors,” but these tend to be a poison/moderator combination or a metal reflector followed by a hydrogenous reflector, which the PNNL results indicate does not cause an increase in reactivity.

A study[4] by researchers at the Russian Federal Nuclear Center- Institute of Technical Physics (RFNC-VNIITF) presented at the International Conference on Nuclear Criticality (ICNC) in 1995 details calculational and experimental investigations of the reflective properties of combined polyethylene (PE) and beryllium. These two reflector materials were chosen due to their superior reflection ability and wide use in the nuclear industry. For reflector thicknesses greater than 4 cm, the study determined that polyethylene backed with beryllium resulted in a 0.7% reactivity increase at the optimal PE thickness of 1-1.5 cm versus a single beryllium reflector.

Based on the results of these studies, the composite reflector effect is believed to be real and experimentally verifiable. It is the aim of this study to design an experiment using the BeRP ball and common reflector materials in combination that will drive it critical. This study could have a profound impact on modern criticality safety practice by alerting practitioners to the potential hazard of composite reflection with everyday reflector materials.

3.0 Methodology

For calculations presented in this report, the Monte Carlo neutron transport code, MCNP5, version 1.51, developed at Los Alamos National Laboratory, was used. Continuous energy ENDF/B-VII.1 cross sections (.80c) were used in all MCNP5 calculations, save for a few minor constituents where ENDF/B-VII cross sections were unavilable. The non-default parameters used for the MCNP5 runs are listed in Table 3-1.

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[3] NEA/NSC/DOC(95)03. *International Handbook of Evaluated Criticality Safety Benchmark Experiments.* September 2011 Edition. Nuclear Energy Agency. Organisation for Economic Cooperation and Development.

[4] Chernuchin, Y.I. et al. *Composite Polyethylene-Beryllium Neutron Reflector: Anomaly of Criticality Safety.* Proceedings of the Fifth International Conference on Nuclear Criticality. Vol 2. Pages 12/30-33. Albuquerque, NM. September 1995.

Table 3-1: Parameters Used in MCNP5 v 1.51 Calculations

Parameter	Description	Value
gen	Number of generations run	1250
npg	Number of neutrons started per generation	10^5
nsk	Number of generations skipped (not included in k_{eff} calculation)	50

Additionally, TSUNAMI-3D, part of the SCALE[5] package, was used to compute energy-dependent sensitivity and uncertainty data for each nuclide in the modeled system using adjoint-based first-order linear perturbation theory. Continuous energy cross sections are not available for use with TSUNAMI, so 238 group ENF/B-VII cross sections (v7-238) were used in all TSUNAMI runs. The non-default parameters used for the TSUNAMI calculations are listed in Table 3-2. TSUNAMI uses Keno V.a for both forward and adjoint calculations, and in order to decrease the uncertainty in the adjoint calculation, additional generations were run.

Table 3-2: Parameters Used in TSUNAMI Calculations

Parameter	Description	Value
gen	Number of generations run	2500
npg	Number of neutrons started per generation	5000
nsk	Number of generations skipped (not included in k_{eff} calculation)	100

[5] SCALE 6: *Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation for Workstations and Personal Computers*. CCC-725. Oak Ridge National Laboratory. June 20XX.

4.0 Feasibility Studies of Composite Reflection Critical Experiments using the BeRP Ball

4.1 BeRP Ball Description

The BeRP ball, as described in ICSBEP evaluation PU-MET-FAST-038[6], is an α-phase sphere of cast plutonium with a mass of 4.484 kg and a diameter of 7.5876 cm. Based on these measured values, the density of the sphere is calculated to be 19.6039 g/cm^3. The α phase plutonium sphere is composed, as presented in PU-MET-FAST-038[7], of 93.284 wt% ^{239}Pu, 5.95 wt% ^{240}Pu, 0.2 wt% ^{241}Pu, 0.028 wt% ^{242}Pu, and 1130 ppm of ^{241}Am. Density of the sphere is 19.6039 g/cm^3. A thin stainless steel cladding surrounds the fissile core. The inner and the outer radii of this cladding are 3.827 and 3.857 cm, respectively. There is a small gap between the fissile hemispheres and the stainless steel cladding. Material compositions and radii found in the detailed model from PU-MET-FAST-013 were used in the BeRP modeling, and are provided in Appendix A.

4.2 Composite Reflectors with Polyethylene

The BeRP ball model was used to investigate the composite reflection effects of polyethylene and twelve different candidate metals: nickel (Ni), iron (Fe), chromium (Cr), titanium (Ti), manganese (Mn), Zirconium (Zr), Tungsten (W), aluminum (Al), lead (Pb), cobalt (Co), copper (Cu), and depleted uranium (U). These specific metals were chosen because they are commonly used as structural materials in nuclear applications. For example, many of these metals are components of stainless steel alloys. In the MCNP model, a layer of polyethylene (PE) of variable thickness was located around the BeRP ball and backed by the metal reflector, which was fixed at 30 cm (infinite) thickness. Figure 4.1 shows a 2D representation of the 3D MCNP geometry used for the calculations. The purple region is the spherical BeRP ball, surrounded by the variable thickness reflector of high density polyethylene (shown in light blue). The gray area is the 30 cm fixed-thickness metallic reflector.

[6] Hutchinson, J., "Plutonium Sphere Reflected by Beryllium," *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, PU-MET-FAST-038, NEA/NSC/DOC (95)03, OECD, September 2012 Edition.

[7] Hutchison, J., et al., *Plutonium Sphere Reflected by Beryllium.* PU-MET-FAST-038, International Handbook of Evaluated Criticality Safety Benchmark Experiments. NEA/NSC/DOC(95)03/I. September 2011.

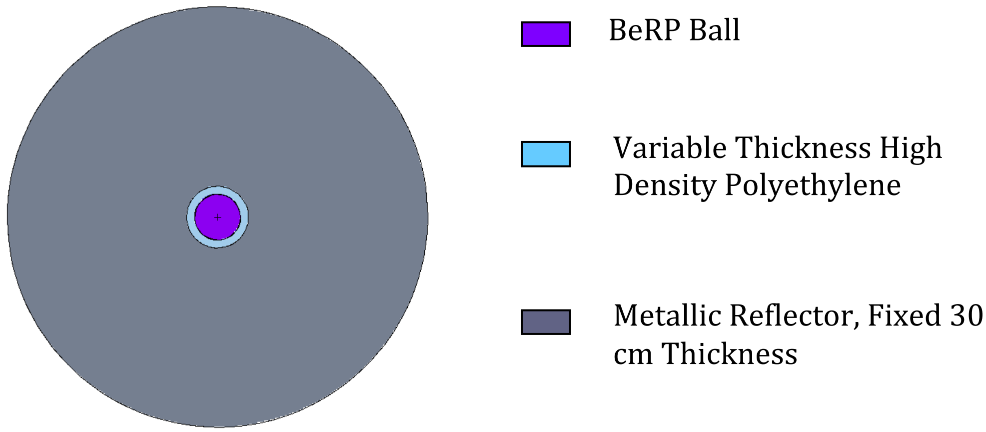


Figure 4.1: MCNP5 Geometry for BeRP Ball Surrounded by Various Composite Reflectors.

Figure 4.2 displays the results from the MCNP5 calculations for composite reflectors with varying polyethylene thickness backed with 30 cm of various metals. Not all metals displayed the composite effect, namely tungsten and cobalt. The highest reactivity for tungsten (black line, shaded circles) and cobalt (purple line, shaded circles) was calculated when there was no polyethylene reflector at all. Depleted uranium and polyethylene composite reflectors (red line, shaded circles) displayed interesting behavior as k_{eff} initially decreases with the addition of polyethylene and then displays a composite reflection increase, taking the configuration just above critical around 2 cm of PE thickness. The initial decrease is likely due to the reduced density of the reflector as DU is replaced with PE and increased absorption as neutron energy is reduced through moderation. All other metals displayed some degree of the composite reflection effect, with reactivity increasing with increasing polyethylene reflector thickness and then leveling off and approaching a keff of 0.9434(2), the reactivity of the BeRP ball reflected by infinite PE alone.

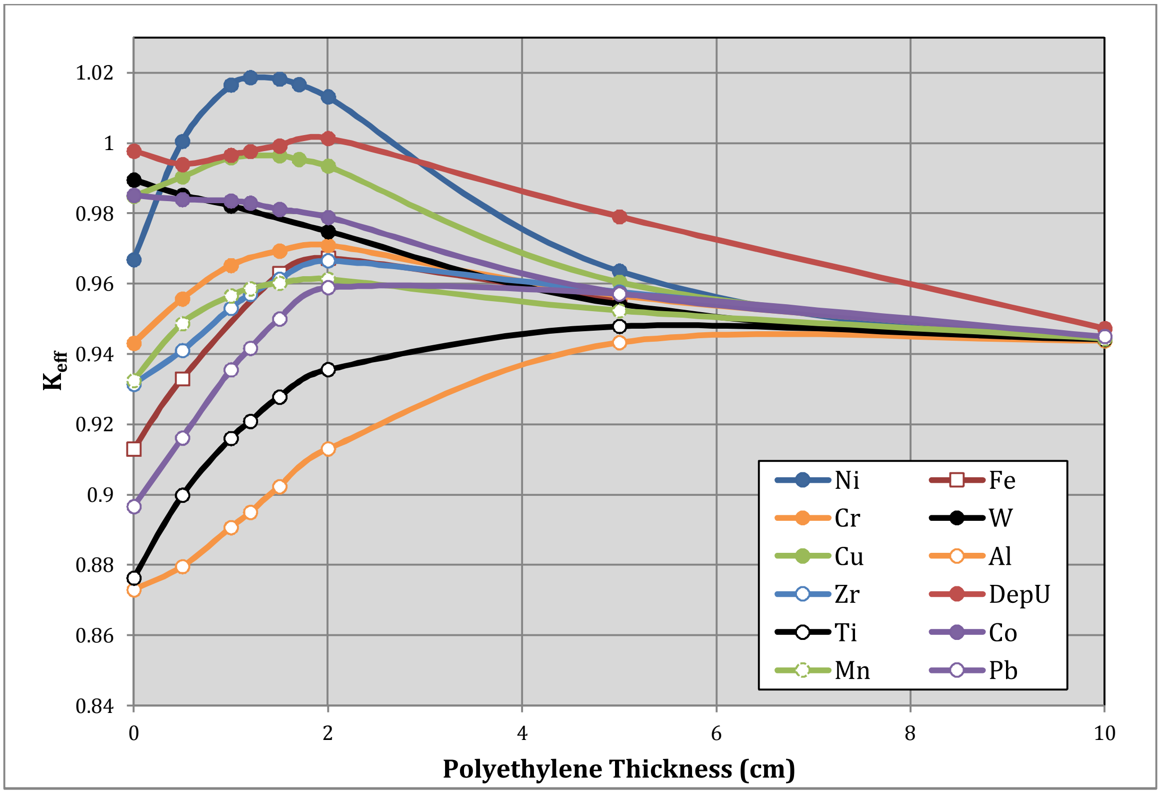


Figure 4.2: K_{eff} of the BeRP Ball as a Function of Varying Thicknesses of Polyethylene Reflection Backed by 30 cm Thick Metallic Reflectors

From the configurations studied, nickel and PE was shown to have the largest effect on BeRP ball reactivity, peaking at a k_{eff} of 1.0186(2) at 1.2 cm of PE. This corresponds to an increase in k_{eff} of approximately 3.5% from the purely nickel reflected case. The only other reflector combination shown to produce a critical configuration was depleted uranium and polyethylene. However, at a peak keff of 1.0013(2), this configuration is likely marginal for a critical experiment when experimental realities (such as reflector gaps) are considered. The other combinations of reflector materials failed to produce a critical configuration with the BeRP ball, but could be candidates for critical reflectors for other fissile cores.

In an attempt to elucidate why nickel is such an effective composite reflector when paired with polyethylene, the nickel scattering cross sections were examined using the Organisation for Economic Cooperation and Development's (OECD) cross section visualization code, JANIS 4.0.[8] JANIS can visualize many different data libraries, including ENDF/B-VII. Figure 4.3 shows nickel total scattering cross section (pink line) as well as the angular differential cross section for backscattering neutrons ($\mu = -1$, red line) as compared to the same cross sections for copper (blue lines). Copper was used for

[8] Organisation for Economic Cooperation and Development. Nuclear Energy Agency. *Java-Based Nuclear Information Software (JANIS), Version 4.0*. Build 5.4.647. September 12, 2013.

comparison with nickel because it did not exhibit as large of a composite reflection effect when paired with polyethylene, as shown above in Figure 4.2 (green line, shaded circles). The macroscopic cross section is plotted to account for varying density and physical nuclear size between the two materials.

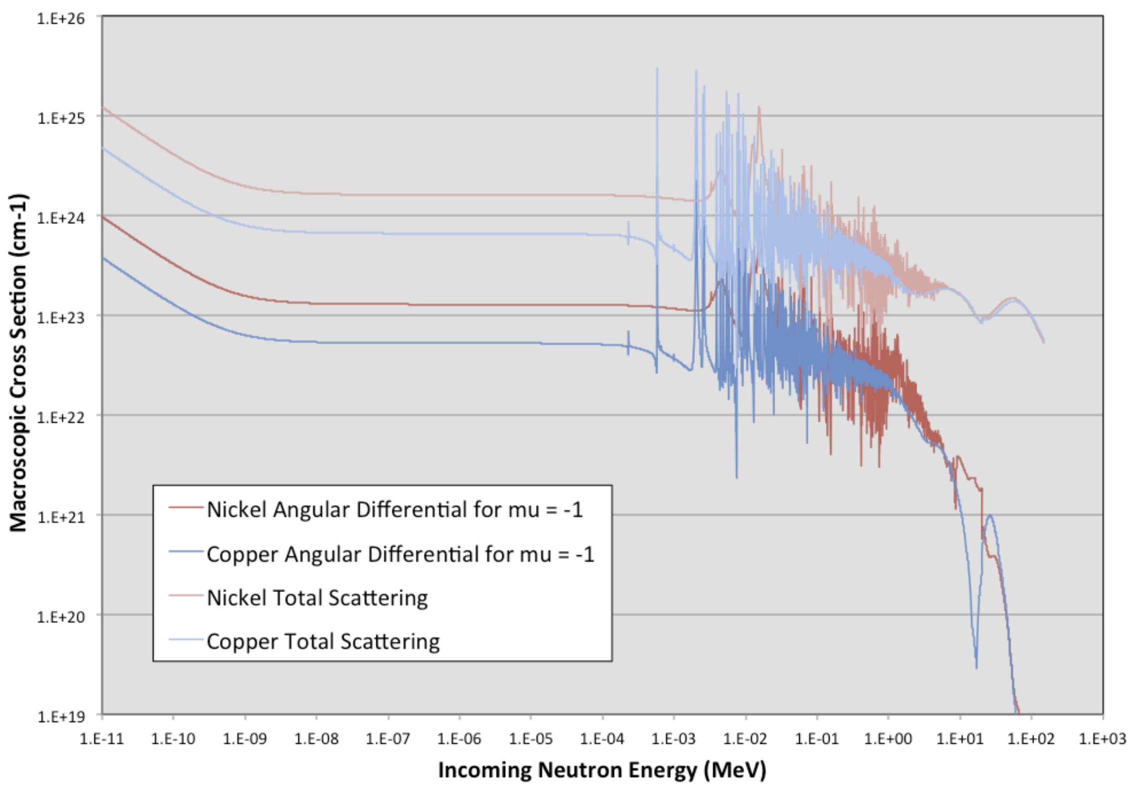


Figure 4.3: Macroscopic Cross Sections (Angular Differential Scattering and Total Scattering) versus Incoming Neutron Energy for Naturally Occurring Nickel and Copper.

As shown by Figure 4.3, in the energy regime expected to be encountered by the reflected BeRP ball system (< 10 MeV), the angular differential cross section appears to track to the total scattering cross section. Considerable resonance behavior is observed in nickel for the total and angular differential scattering cross section in the fast neutron energy regime (> 0.1 MeV) up to about 10 MeV, which is not seen for copper. Additionally, at lower energies (< 5 keV), both nickel cross sections are considerably higher than copper, and neutrons at these energies would be 4-5 times more likely to be scattered in nickel.

4.3 Polyethylene and Nickel Composite Reflectors

Figure 4.2 shows that the highest k_{eff} for the polyethylene/nickel composite reflector was attained at 1.2 cm of PE thickness with 30 cm of nickel reflector. In an attempt to understand why 1.2 cm of PE is the optimal thickness for a composite reflector with nickel, an additional feature of MCNP5, the f1 current tally, was used. The f1 tally logs the each neutron that crosses a user-defined surface in the MCNP5 geometry. This neutron current can be binned in a number of ways, including by energy and the cosine of the angle of approach (μ). Figure 4.4 displays the result of the MCNP5 f1 tally for neutrons entering the BeRP ball from the reflector ($-1 \leq \mu \leq 0$) for various thicknesses of PE backed by a fixed 30 cm of nickel reflection. Figure 4.5 displays the same information, but as a cumulative distribution function. As seen in the graphs, the neutron spectrum softens as PE is added, shifting from an initially very fast spectrum with no PE (red lines) to a largely thermal spectrum as PE thickness is increased (blue lines). The optimal case of 1.2 cm of PE, which produced the highest keff as described in Section 4.2, is shown as the purple line in both graphs.

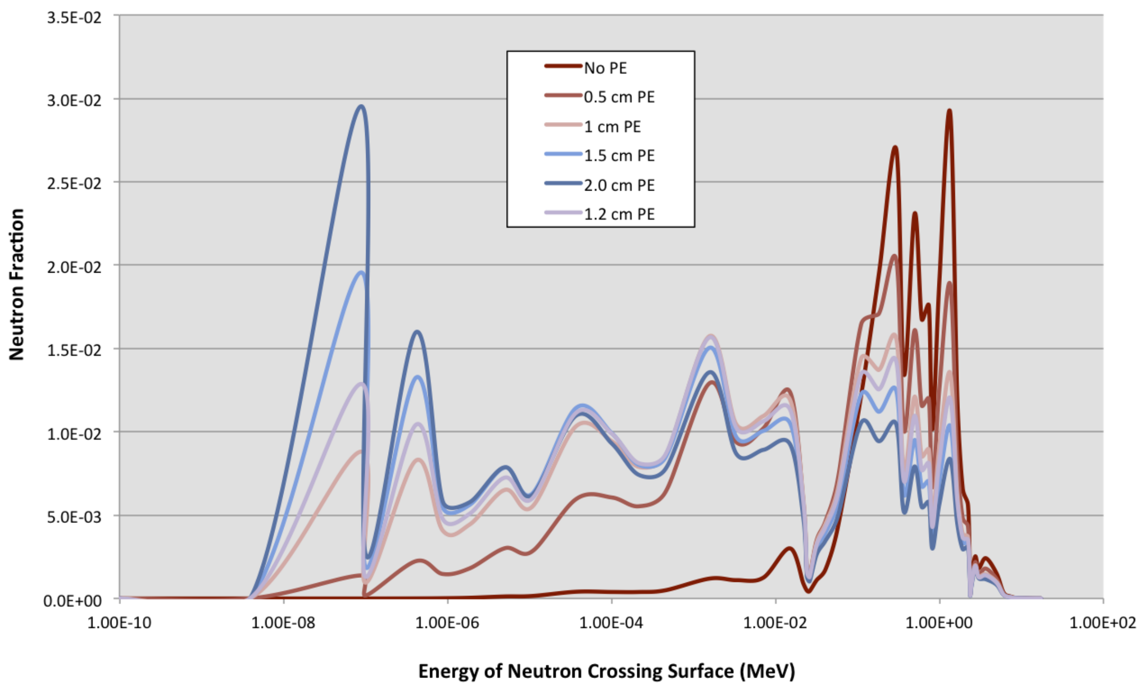


Figure 4.4: Spectrum of Neutrons Returning to BeRP Ball from Composite Reflectors Comprised of Varying Thickness of Polyethylene PE Backed by 30 cm of Nickel

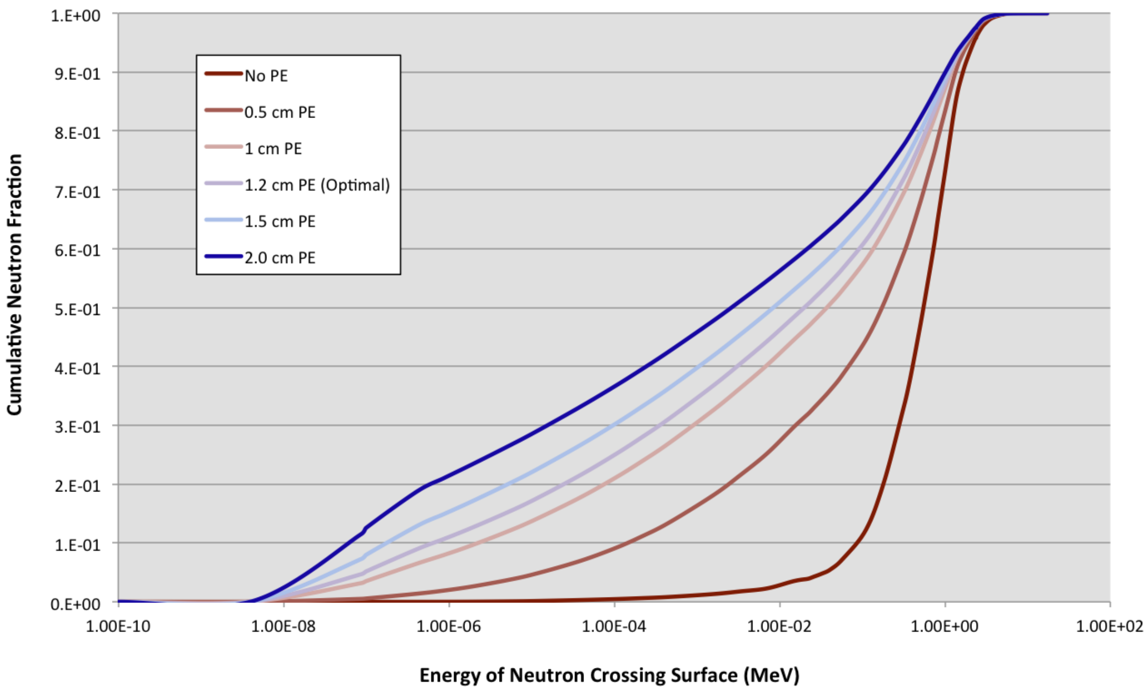


Figure 4.5: Cumulative Distribution Function of Energy of Neutrons Returning to BeRP Ball from Composite Reflectors Comprised of Varying Thickness of Polyethylene PE Backed by 30 cm of Nickel

Since ^{239}Pu fission cross section increases with decreasing neutron energy, the fact that the optimal thickness of PE produces a largely intermediate-energy neutron spectrum (as shown by Figures 4.4 and 4.5) at first appears problematic. Two hypotheses are put forward to explain this result. First is that while thicker PE layers return lower energy neutrons to the BeRP ball, their overall percentage of return is less due to parasitic absorption in the thicker layer of PE. Second, a more thermal spectrum of neutrons would likely fission very quickly in the outer layer of the BeRP ball, resulting in much higher leakage fractions than if the neutrons had enough energy to migrate to the center of the ball. A combination of these two effects likely explains why the optimal neutron energy spectrum has a large intermediate fraction.

4.4 Reducing Nickel Reflector Thickness

All preceding calculations were completed using a fixed 30 cm of nickel reflector. Additional MCNP5 calculations were completed that looked at the effect of reducing the nickel reflector. The inner PE thickness was maintained at 1.2 cm and the outer Ni reflector thickness was varied. The results are tabulated in Table 4-1 and are plotted in Figure 4.6.

Table 4-1: BeRP Ball k_{eff} for PE/Nickel Composite Reflectors for Varying External Ni Reflector Thickness

Case ID	Thickness of PE	Thickness of Ni	$k_{eff} \pm \sigma$
ni0	1.2 cm	0 cm	0.8237 ± 0.0002
ni3	1.2 cm	3 cm	0.9345 ± 0.0002
ni5	1.2 cm	5 cm	0.9629 ± 0.0002
ni10	1.2 cm	10 cm	0.9934 ± 0.0002
ni15	1.2 cm	15 cm	1.0064 ± 0.0002
ni20	1.2 cm	20 cm	1.0128 ± 0.0002
ni25	1.2 cm	25 cm	1.0167 ± 0.0002
ni30	1.2 cm	30 cm	1.0186 ± 0.0002

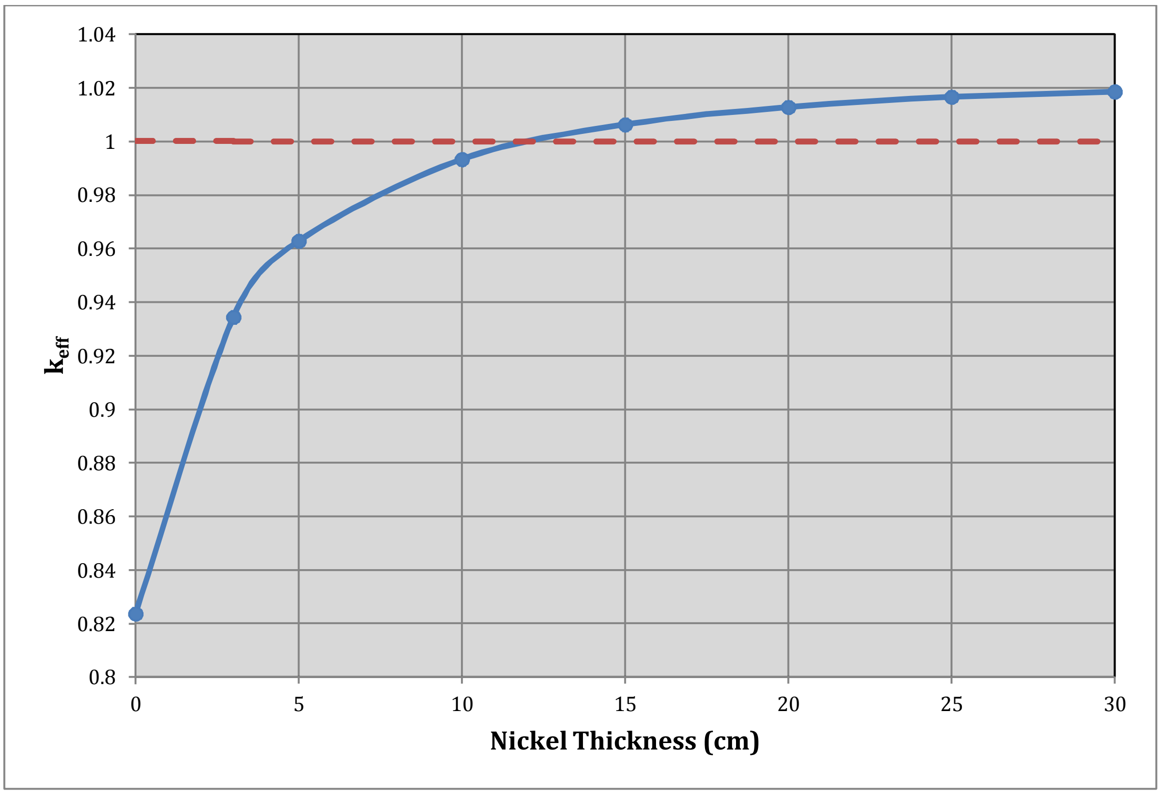


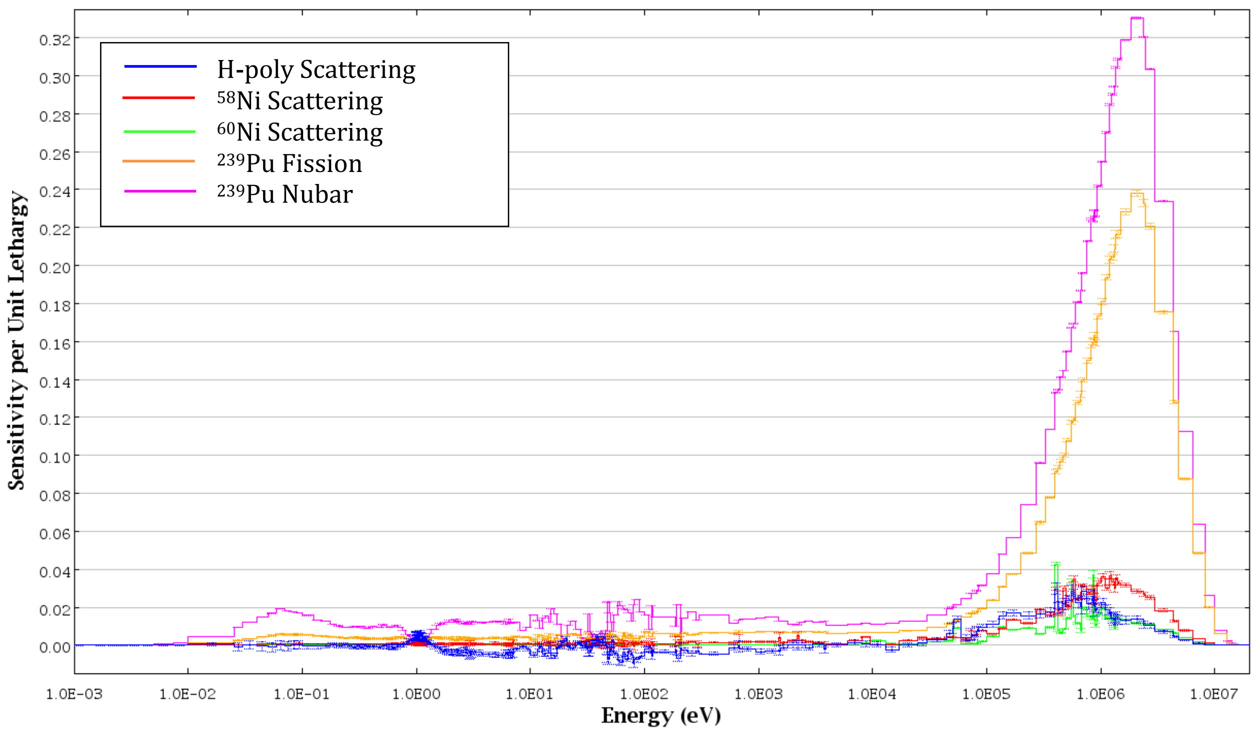
Figure 4.6: K_{eff} of the BeRP Ball as a Function of Varying Thicknesses of Nickel Outer Reflection with a Fixed 1.2 cm Inner Polyethylene Reflector

With 1.2 cm of PE next to the BeRP ball, the thickness of nickel required to achieve criticality is approximately 12 cm, as shown in Figure 4.6. With an external nickel thickness of 20 cm, the BeRP composite reflector system has excess reactivity greater than 1%. Therefore, it is likely that the additional 10 cm of reflector, which would be the most costly to fabricate and the most cumbersome to use in the experiment, is unnecessary.

5.0 Sensitivity, Uncertainty, and Bias Analysis

5.1 TSUNAMI Sensitivity Calculations

TSUNAMI-3D sensitivity analysis was run for the case of 1.2 cm of PE backed with 20 cm of nickel reflector to ensure the designed experiment would serve as a test of the nickel and polyethylene cross sections. The TSUANMI module perturbs the cross sections used in the model by 1% and analyzes the effect for each cross section for each isotope used in the material compositions of the model. The results of the sensitivity calculations are displayed in the following table and graph.



Cross Section Reaction	Total Sensitivity*
H-poly Scattering	0.0997
^{58}Ni Scattering	0.1076
^{60}Ni Scattering	0.0505
^{239}Pu Fission	0.6314
^{239}Pu Nubar	0.9622

* The total sensitivity is reported as the positive sensitivity plus the absolute value of the negative sensitivity.

Figure 5.1: TSUNAMI Results Showing Sensitivity Per Unit Lethargy for the Highest Contributing Reactions for the BeRP Ball Reflected by 1.2 cm of Polyethylene Backed with 20 cm of Nickel. The integral total sensitivity is given in the table below the graph.

As expected, the highest sensitivity of the BeRP/composite reflector system was determined to be to the ^{239}Pu fission cross section and nubar, as they have the highest impact on the number of neutrons available in the system. A 1% change in the nubar value would be expected to result in a 1% change in k_{eff}. The scattering cross section of the two main naturally occurring isotopes of nickel, ^{58}Ni and ^{60}Ni, contributed a sensitivity of 0.1581 (0.15% change in k_{eff}), and the system also showed sensitivity to the hydrogen scattering cross section (present in the polyethylene). However, TSUNAMI does not include perturbation analysis of the scattering angular differential cross sections, which would also likely have a significant contribution to the sensitivity of the reflected BeRP system.

5.2 Estimation of Calculational Bias

In an effort to quantify the calculational bias introduced by MCNP5 and the cross section libraries used in this composite reflection feasibility study, the International Criticality Safety Benchmark Evaluation Project handbook was examined for fast experimental benchmarks that used polyethylene or nickel as a reflector. Table 5-1 lists the relevant nickel reflected fast critical configurations (a total of 7) and Table 5-2 shows the relevant PE reflected configurations (a total of 19). These benchmark cases were run using MCNP and ENDF/B-VII.1 data libraries as part of the LLNL Nuclear Criticality Safety Division's safety software validation effort, which is documented in Criticality Safety Memorandum (CSM) 1664[9] and 1665[10]. The pertinent results (k_{eff} and uncertainty) of these MCNP5 calculations are shown in the tables below. Each benchmark result is normalized to the delayed critical condition (k_{eff} = 1) as follows:

$$k_{normalized} = (k_{calculated} - k_{expected}) + 1$$

where $k_{calculated}$ is the result from the MCNP5 run and $k_{expected}$ is the expected experimental k_{eff} as reported by the ICSBEP evaluation. The associated uncertainty ($\sigma_{combined}$) for each benchmark result becomes:

$$\sigma_{combined} = \sqrt{(\sigma_{calculated})^2 + (\sigma_{expected})^2}$$

Only $k_{normalized}$ and $\sigma_{combined}$ are reported in the following tables. The calculated and expected values are reported in CSM 1664 and 1665.

[9] Kim, S.S. *Validation of MCNP5(Version 1.51) on Teal for General Application to Plutonium Systems.* Lawrence Livermore National Laboratory. CSM 1664. February 3, 2014.
[10] Kim, S.S. *Validation of MCNP5 (Version 1.51) on Teal for General Application to Highly Enriched Uranium Systems.* Lawrence Livermore National Laboratory. CSM 1665. February 11, 2014.

Table 5-1: MCNP5 Results for Fast Benchmark Cases with Nickel Reflection

Benchmark ID	Case	Title	Normalized Calculated k_{eff}	Combined Uncertainty
HEU-MET-FAST-084	11	*HEU Metal Cylinders with Mg, Ti, Al, Graphite, Mild Steel, Ni, Cu, Co, Mo, Natural Uranium, W, Be, Al Oxide, Mo Carbide, and Polyethylene Reflectors*	1.0003	0.0018
PU-MET-FAST-014	1	*Nickel-Reflected Array of Plutonium Fuel Rods*	1.0024	0.0032
PU-MET-FAST-045	1	*Critical Experiments Performed for LAMPRE, the Los Alamos Molten Plutonium Reactor*	0.9992	0.0034
	2		1.0063	0.0034
	3		1.0062	0.0035
	4		1.0058	0.0035
	5		1.0054	0.0036

Table 5-2: MCNP5 Results for Fast Benchmark Cases with Polyethylene Reflection

Benchmark ID	Case	Title	Normalized Calculated k_{eff}	Combined Uncertainty
HEU-MET-FAST-007	35	*Uranium Metal Slabs Moderated With Polyethylene, Plexiglas, and Teflon*	0.9932	0.0020
HEU-MET-FAST-011	1	*Sphere of Highly Enriched Uranium Reflected by Polyethylene*	1.0003	0.0018
HEU-MET-FAST-020	1	*Polyethylene-Reflected Spherical Assembly of ^{235}U(90%)*	1.0010	0.0043
HEU-MET-FAST-031	1	*Spherical Assembly of ^{235}U(90%) With Central Area of Polyethylene and 17.45-Cm Polyethylene Reflector*	1.0048	0.0060
HEU-MET-FAST-037	1	*Two Heterogeneous Cylinders Of Highly Enriched Uranium, Polyethylene, and Depleted Uranium with Polyethylene or Polyethylene and Cadmium Reflector*	1.0037	0.0014
HEU-MET-FAST-084	12	*HEU Metal Cylinders with Mg, Ti, Al, Graphite, Mild Steel, Ni, Cu, Co, Mo, Natural Uranium, W, Be, Al Oxide, Mo Carbide, and Polyethylene Reflectors*	1.0043	0.0021

Benchmark ID	Case	Title	Normalized Calculated k_{eff}	Combined Uncertainty
PU-MET-FAST-003	102	*Unmoderated Plutonium Metal Button Array*	0.9962	0.0031
	104		0.9967	0.0031
PU-MET-FAST-024	1	*Polyethylene-Reflected Spherical Assembly of ^{239}Pu (d, 98%)*	1.0002	0.0021
PU-MET-FAST-027	1	*Polyethylene-Reflected Spherical Assembly of ^{239}Pu(D, 89%)*	1.0032	0.0023
PU-MET-FAST-031	1	*Polyethylene-Reflected Spherical Assembly of ^{239}Pu(A, 88%)*	1.0048	0.0022

The results from Tables 5-1 and 5-2 are portrayed graphically in Figure 5.1. The normalized calculated k_{eff}s ($k_{normalized}$), with their corresponding combined uncertainties (error bars), are plotted versus the MCNP5-calculated Energy of the Average Neutron Lethargy Causing Fission (EALCF). The nickel benchmarks (dark circles) are all fast systems with EALCFs between 0.1 and 1 MeV, while the PE benchmarks (open circles) are more varied in characteristic fission energy (down to approximately 2 keV). The nickel and PE biases were calculated by averaging all calculated normalized k_{eff}s and determining the difference in the average from the delayed critical condition ($k_{eff} = 1$).

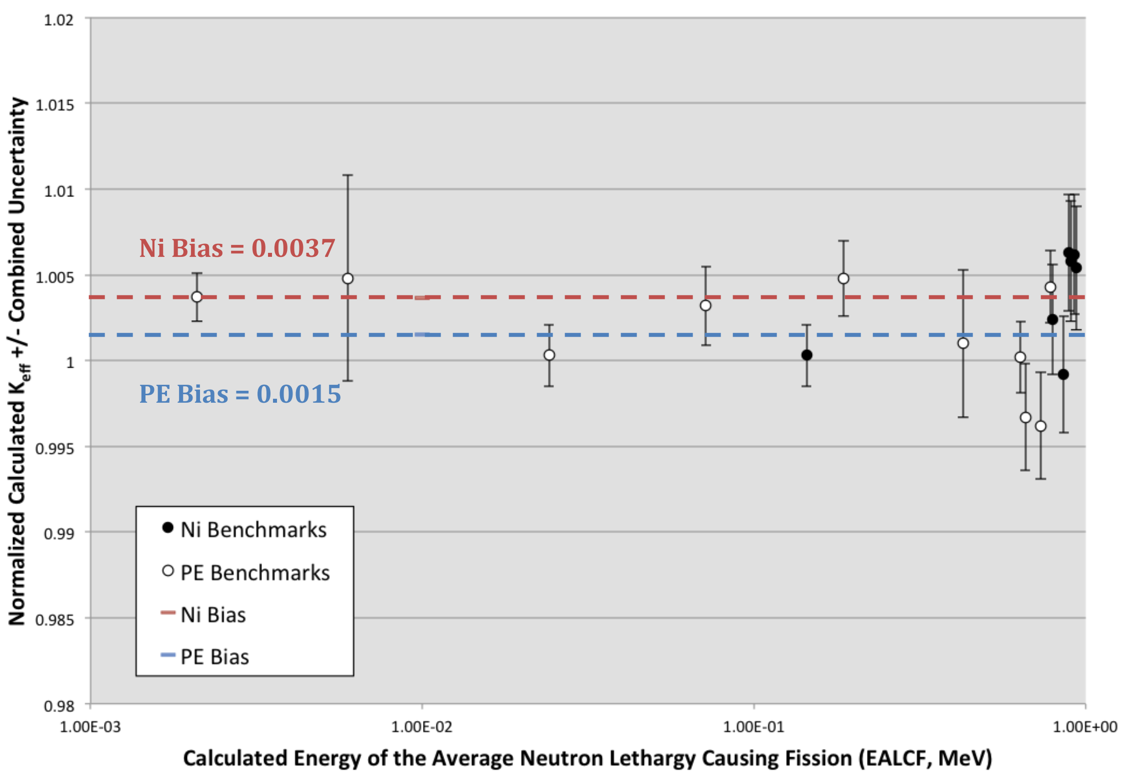


Figure 5.1: MCNP5 ENDF/B-VII k_{eff} Results Versus Energy of the Average Neutron Lethargy Causing Fission for Fast ICSBEP Benchmark Experiments using Nickel or Polyethylene as a Reflector

As shown in Figure 5.1, there is a small positive bias (0.0037) for nickel acting as a reflector when calculated with MCNP5 using ENDF/B-VII.1 cross sections. The bias is much lower for polyethylene (0.0015). However, the results represent a small sample set, especially for nickel, owing to the lack of appropriate fast experimental benchmarks. Even taking into account this positive bias, the amount of excess reactivity in the composite reflector calculations presented in Section 4.0 for polyethylene and nickel instills confidence that a critical configuration with the BeRP ball can be constructed.

6.0 Conclusions

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As shown in Section 4.0, polyethylene backed by nickel was calculated by MCNP5 to be the most reactive reflector condition around the BeRP Ball of composite reflectors studied. The optimal polyethylene thickness was found to be 1.2 cm and the corresponding critical nickel thickness is approximately 12 cm. With a nickel thickness of 20 cm, the excess reactivity of the system, as calculated by MCNP5, is 0.0128.

An investigation of ICSBEP fast critical benchmarks with polyethylene and nickel reflection showed a small positive bias to the MCNP5 calculations. Even when taking this bias into account (0.005 combined Δk), the level of excess reactivity calculated for 1.2 cm of PE and 20 cm of nickel surrounding the BeRP ball provides confidence that a critical assembly can be achieved.

Based on these preliminary findings, CED-2 (Final Design) will focus on design of experimental equipment such as the polyethylene and nickel shells and the support structure for the assembly on a critical machine.

Appendix A: Material Compositions Used in MCNP5 Calculations

A.1 Number Densities for BeRP Ball.

Isotope	Number Density (atoms/barn-cm)
^{238}Pu	9.8709E-06
^{239}Pu	4.6068E-02
^{240}Pu	2.9121E-03
^{241}Pu	9.7793E-05
^{242}Pu	1.3590E-05
Pu Total	**4.9102E-02**
^{241}Am	5.5350E-05
^{54}Fe	1.2356E-07
^{56}Fe	1.9396E-06
^{57}Fe	4.4794E-08
^{58}Fe	5.9613E-09
Fe Total	**2.1139E-06**
Ga	5.6723E-05
Be	6.5498E-07
Al	1.0939E-06
^{58}Ni	3.4235E-07
^{60}Ni	1.3187E-07
^{61}Ni	5.7329E-09
^{62}Ni	1.8275E-08
^{64}Ni	4.6567E-09
Ni Total	**5.0288E-07**
Mo	1.1075E-06
^{206}Pb	3.4816E-08
^{207}Pb	3.1927E-08
^{208}Pb	7.5700E-08
Pb Total	**1.4244E-07**
^{10}B	1.0811E-07
^{11}B	4.3789E-07
^{28}Si	9.6922E-07

Isotope	Number Density (atoms/barn-cm)
^{29}Si	4.9212E-08
^{30}Si	3.2440E-08
Si Total	**1.0509E-06**
^{63}Cu	6.4252E-08
^{65}Cu	2.8638E-08
Cu Total	**9.2891E-08**
^{107}Ag	2.8368E-08
^{109}Ag	2.6355E-08
Ag Total	**5.4723E-08**
Bi	2.8246E-08
Na	1.2838E-05
Ca	8.8370E-07
Zn	4.5136E-07
^{106}Cd	6.5640E-09
^{108}Cd	4.6735E-09
^{110}Cd	6.5587E-08
^{111}Cd	6.7215E-08
^{112}Cd	1.2671E-07
^{113}Cd	6.4169E-08
^{114}Cd	1.5087E-07
^{116}Cd	3.9331E-08
Cd Total	**5.2512E-07**
Mg	2.4286E-07
^{50}Cr	2.4663E-08
^{52}Cr	4.7561E-07
^{53}Cr	5.3930E-08
^{54}Cr	1.3424E-08
Cr Total	**5.6762E-07**
Zr	6.4707E-06
Sn	2.4862E-07
C	2.2607E-04

A.2 Number Densities for 304 SS Cladding of BeRP Ball.

Isotope	**Number Density (atoms/barn-cm)**
^{50}Cr	7.4030E-04
^{52}Cr	1.4276E-02
^{53}Cr	1.6188E-03
^{54}Cr	4.0295E-04
Cr Total	**1.7038E-02**
^{54}Fe	3.4244E-03
^{56}Fe	5.3756E-02
^{57}Fe	1.2415E-03
^{58}Fe	1.6522E-04
Fe Total	**5.8587E-02**
^{58}Ni	5.0028E-03
^{60}Ni	1.9271E-03
^{61}Ni	8.3776E-05
^{62}Ni	2.6705E-04
^{64}Ni	6.8049E-05
Ni Total	**7.3487E-03**
C	1.5528E-04
Mn	8.4872E-04
^{28}Si	7.6559E-04
^{29}Si	3.8873E-05
^{30}Si	2.5625E-05
Si Total	**8.3009E-04**
P	3.3871E-05
S	2.1809E-05

A.3 Material Compositions for Moderating and Reflecting Materials.

Element/Isotope	Weight Percent
Polyethylene	**0.967 g/cm^3**
^{1}H(poly)	2*
Carbon	*1**
^{12}C	98.89
^{13}C	1.11
Nickel	**8.9 g/cm^3**
^{58}Ni	67.395
^{60}Ni	26.653
^{61}Ni	1.173
^{62}Ni	3.788
^{64}Ni	0.991
Iron	**7.87 g/cm^3**
^{54}Fe	5.699
^{56}Fe	91.870
^{57}Fe	2.141
^{58}Fe	0.290
Chromium	**7.19 g/cm^3**
^{50}Cr	4.174
^{52}Cr	83.700
^{53}Cr	9.673
^{54}Cr	3.308
Tungsten	**19.2 g/cm^3**
^{182}W	26.028
^{183}W	14.210
^{184}W	30.834
^{186}W	28.928
Copper	**8.96 g/cm^3**
^{63}Cu	68.499
^{65}Cu	31.501
Al	**2.7 g/cm^3**
^{27}Al	100
Titanium	**4.54 g/cm^3**
^{46}Ti	0.0825*
^{47}Ti	0.0744*
^{48}Ti	0.7372*
^{49}Ti	0.0541*
^{50}Ti	0.0518*
Manganese	**7.43 g/cm^3**
^{55}Mn	100
Cobalt	**8.8 g/cm^3**
^{63}Co	0.6917*
^{65}Co	0.3083*
Lead	**11.34 g/cm^3**
^{204}Pb	0.014*
^{206}Pb	0.241*
^{207}Pb	0.221*
^{208}Pb	0.524*
Depleted Uranium	**18.9 g/cm^3**
^{235}U	0.25
^{238}U	99.75

* Atom fraction instead of weight percent.

Appendix B: Sample MCNP5 Input Files

```
BeRP Ball with 1.2 cm PE backed with 30 cm Ni Reflector
c         Plutonium sphere
1     1 4.94964E-02 -1 imp:n=1
c     Cladding
2     0   1 -2 imp:n=1
3         2 8.48638E-02  2 -3 imp:n=1
c
c      replaced by HDPE by SS Kim
4         9 -0.967     3  -11 imp:n=1
c
c         Ni outer reflector
5   8  -8.9  11 -21 imp:n=1
c
c
c         Other air in the system
6   0     21
         imp:n=0

c         BERP ball
1          so  3.7938     $ Plutonium sphere OR
2          so  3.82778    $ SS clad IR
3          so  3.85826    $ SS clad OR
11      so  5.35826     $ PE
21      so  35.358   $ Ni outer shell OR

mode n
f1:n 1
c0  -0.866 -0.5 0 0.5 0.866 1 T
f11:n 11
c  Neutron Groups
e0   1.00000E-11  1.00000E-10  4.14000E-09  8.76000E-08
    1.00000E-07  4.14000E-07  8.76000E-07  1.86000E-06
    5.04000E-06  1.07000E-05  3.73000E-05  1.01000E-04  2.14000E-04
    4.54000E-04  1.58000E-03  3.35000E-03  7.10000E-03  1.50000E-02
    2.19000E-02  2.42000E-02  2.61000E-02  3.18000E-02  4.09000E-02
    5.74000E-02  1.11000E-01  1.83000E-01  2.97000E-01  3.69000E-01
    4.98000E-01  6.08000E-01  7.43000E-01  8.21000E-01  1.00000E+00
    1.35000E+00  1.65000E+00  1.92000E+00  2.23000E+00  2.35000E+00
    2.37000E+00  2.47000E+00  2.73000E+00  3.01000E+00  3.68000E+00
    4.97000E+00  6.07000E+00  7.41000E+00  8.61000E+00  1.00000E+01
    1.22000E+01  1.42000E+01  1.73000E+01
ksrc 0 0 0
kcode 10000 1 50 1250
```

```
print
c   mat1- alpha phase Pu from Pu-MET-FAST-038
m1   94238    9.87090E-06
     94239    4.60684E-02
     94240    2.91208E-03
     94241    9.77932E-05
     94242    1.35904E-05
     95241    5.53502E-05
     26054    1.23559E-07
     26056    1.93962E-06
     26057    4.47942E-08
     26058    5.96128E-09
     31000    5.67230E-05
     4009     6.54982E-07
     13027    1.09387E-06
     28058    3.42347E-07
     28060    1.31871E-07
     28061    5.73286E-09
     28062    1.82747E-08
     28064    4.65669E-09
     42000    1.10747E-06
     82206    3.48162E-08
     82207    3.19268E-08
     82208    7.56999E-08
     5010     1.08108E-07
     5011     4.37894E-07
     14028    9.69216E-07
     14029    4.92122E-08
     14030    3.24403E-08
     29063    6.42525E-08
     29065    2.86382E-08
     47107    2.83677E-08
     47109    2.63550E-08
     83209    2.82459E-08
     11023    1.28379E-05
     20000    8.83702E-07
     30000.42c 4.51356E-07
     48106    6.56395E-09
     48108    4.67353E-09
     48110    6.55870E-08
     48111    6.72149E-08
     48112    1.26711E-07
     48113    6.41692E-08
     48114    1.50866E-07
     48116    3.93312E-08
     12000    2.42865E-07
```

```
      24050       2.46632E-08
      24052       4.75606E-07
      24053       5.39299E-08
      24054       1.34243E-08
      40000       6.47070E-06
      50000.42c 2.48624E-07
      6000        2.26068E-04
c Material 2: 304 SS Cladding from PU-MET-FAST-038
m2        24050 7.40303E-04
      24052       1.42760E-02
      24053       1.61878E-03
      24054       4.02949E-04
      26054       3.42442E-03
      26056       5.37561E-02
      26057       1.24146E-03
      26058       1.65216E-04
      28058       5.00281E-03
      28060       1.92706E-03
      28061       8.37757E-05
      28062       2.67054E-04
      28064       6.80494E-05
      6000        1.55280E-04
      25055       8.48717E-04
      14028       7.65589E-04
      14029       3.88730E-05
      14030       2.56248E-05
      15031       3.38707E-05
      16000       2.18086E-05
c    Nickel density 8.9 g/cc
m8   28058  68.0769
     28060  26.2231
     28061  1.1399
     28062  3.6345
     28064  0.9256
c    Polyethylene density=0.967 g/cc
m9   1001 2
     6000 1
mt9  poly
```